Modeling of thin layer hot air-infrared drying of green peas

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Abstract: The drying characteristics of green peas during combined hot air-infrared drying were examined. The experiments were carried out for combination of four infrared power intensities (0, 0.2, 0.4 and 0.6 W/cm^2), three levels of drying air velocity (0.5, 1 and 1.5 m/s), and three levels of drying air temperatures (30 ℃,40 ℃ and 50 ℃). Among several models fitted to the experimental data, the Three Term model was introduced to be the most appropriate model. To predict moisture ratio, drying constants of the model were correlated with drying parameters namely, drying air velocity, drying air temperature and infrared power intensity. The statistics indices of 99.7%, 0.000121, 0.0000 and 0.000121 for R^2, χ^2, MBE and RMSE were obtained for the Three Term model, respectively. Application of infrared radiation in conjunction with hot air drying led to higher drying rate in comparison with the conventional hot air drying. The effective moisture diffusivity for several drying conditions were calculated in the range from 1.39×10^{-10} to 5.72×10^{-10} m^2/s.

Keywords: hot air-infrareddrying, effective moisture diffusivity, thin layer drying, green peas

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1 Introduction

Greenpeas is one of the most important sources of human and animal nutrition. In food industry, green peas is widely used to produce canned peas. Green peas can be harvested at the moisture of about 75% (d.b.) but for safe storage the harvested grains should be dried to less than 25% moisture content.

Infrared radiation (IR) heating involves the exposure of a material to electromagnetic radiation in the wave length range of 0.8- 1000 *l*m. IR drying is fundamentally different from convective drying where the material is dried directly by absorption of IR energy rather than transfer of heat from the air (Bal et al., 1970). IR radiation drying has significant advantages over conventional drying. The advantages are versatility, simplicity of the equipment, easy accommodation of IR heating with convective, conductive and microwave heating, fast transient response and significant energy saving (Momenzadeh et al., 2011). Many researchers reported that, though IR heating provides a rapid means of heating and drying, it is attractive for only surface heating application. As the IR energy is absorbed on the surface, it allows only a shallow layer to be dried(Farkas et al., 2000). The optimum radiation intensity and grain bed depth was found to lie between 3100 and 4290 W/cm^2 and 12 and 16 mm, respectively (CakmakandYildiz, 2011).

Several researchers have worked on the conventional hot air drying of food materials such as rough rice (Hacihafizog et al., 2008), green beans (SahinandSumnu, 2006), soybeans (Hutchinson andOtten, 1983; KiticandViollaz, 1984) and canola (Zare et al., 2009). All studies showed that the application of the conventional drying methods consumes long drying time

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and high amount of energy. Application of infrared heating in conjunction with the hot air drying would lead to a reduction in drying time. Several studies have been performed in this way from which the works Afzal et al. (1999) studied on the drying of Barley with hot air and combined infrared-hot air methods. The combined infrared-hot air drying caused a significant reduction in drying time in comparison with the conventional drying (Afzal et al., 1999). Afzal and Abe studied on the drying of tomato with combined infrared-hot air method. The combined infrared-hot air drying were carried out at the power densities of 0.125, 0.25, 0.375 and 0.5 W/cm^2,and air velocity of 0.3, 0.5 and 0.7 m/s by the use of relative humidity 36% and 62%. So, the drying rate of potato depends on power densities and free from relative humidity (Afzal and Abe, 1999). Hebbar et al. (2004)studied on the drying of carrot and potato with hot air combined infrared-hot air methods. The combined infrared-hot air drying caused a significant in drying time and energy consumption of about 48% and 63% in comparison with the conventional drying (Hebbar et al., 2004).Zare et al. (2015)have recently showed that in rough rice drying by infrared-assisted hot air dryer, the experimental factors of IR intensity, temperature and air velocity, significantly affect bending strength of the brown rice kernel, percentage of cracked kernels, drying time and specific energy consumption (Zare et al., 2015). Some other experimental investigations have been done on the drying of peas (Hatamipour and Mowla, 2003; Sahin et al., 2013).Conventional drying of green peas consumes a large amount of energy and time. By adding infrared heating which leads to uniform generation of heat through the volume of each grain, the drying time decreases significantly. For mathematical modeling of such dryers, one needs to be aware of the kinetics of hot air-infrared drying of a single kernel which plays the role of an element for bulk grains. A thin layer drying equation can be considered as a single kernel drying equation in predicting the moisture content at any time of drying (Brooker et al., 1992). So, from the mathematical point of view, there is a need to find the thin layer drying equation undergoing hot air-infrared treatment for agriculture grains and seeds. Several studies have been done on hot air-infrared thin layer drying of food materials. In the most cases the moisture content of food material was predicted according to infrared power intensities (W/cm^2).

In the present study, the thin layer drying equations were determined according to air temperature and air velocity as well as infrared power intensity at the surface of grains. As far as we know there is no information about hot air-infrared thin layer of green peas.

Therefore, the aims of this study are as:

- To study the effect of the air temperature, air velocity and infrared power intensity on the drying kinetics of green peas.
- Determination of a thin layer drying equation for green peas undergoing hot air-infrared drying.
- Determination of the effective moisture diffusivity for several drying conditions.

2 Materials and methods

2.1 Drying experiments

Fresh green peas was purchased from a farm near Shiraz and used for the study without any pretreatment. Before the drying experiments, samples were stored at 4 ℃-5 ℃ in a refrigerator for about 72 h for equilibration of moisture content. The initial moisture content of green peas kernels determined by standard oven drying method at 105 ℃ for 24 h and it was in the range of 75% (d.b.).

The average diameter of peas kernels was measured as 10.5 mm by a micrometer. During all tests, the thickness of the bed was equal to a single peas kernel diameter.

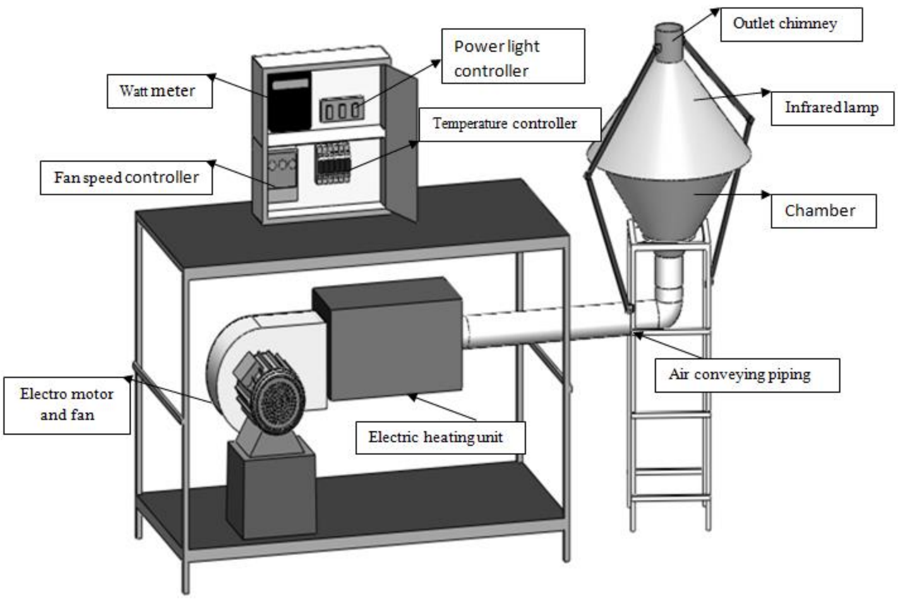

Figure 1 Schematic of the apparatus

A pilot-scale infrared-hot air dryer was designed and implemented for drying of samples. A schematic of this apparatus is presented in Figure 1. The bed was equipped with a perforated Teflon distributer bed to provide a uniform air flow. In addition, the system consisted of a variable speed centrifugal fan controlled by an inverter (N50-007SF, Korea), two 1- kW and three 0.5- kW electric preheaters, and a temperature controller (SU-105IP, Samwon Engineering, Korea) used to keep the inlet air temperature at a constant value. The air velocity approaching the bed was measured using a Testo 435 (Germany) hotwire anemometer with an accuracy of 0.03 m/s. The different infrared radiations were produced by three 250W infrared lights (OSRAM Company, Slovakia). Drying characteristics of green peas in thin layer from having initial moisture content of 75%±0.5% (d.b.) was studied in a hot air dryer assisted by infrared heating when moisture content decreased to 25%±0.5% (d.b.). Experimental factors included drying air temperatures (30℃, 40℃ and 50℃), infrared power intensity (0, 0.2, 0.4 and 0.6 W/cm^2) and drying air velocity (0.5, 1 and 1.5 m/s). The experiments were conducted in three replications for combinations of different levels of factors.

During each drying experiment, sample of green peas was placed in the drying bed and the moisture loss was periodically measured by taking out the bed and weighing it on a digital balance (GF-600, A&D Company, Japan; accuracy, 0.001 g) in less than 10 s.In addition, the temperature and relative humidity of inlet and outlet air were measured using a Testo 435 with an accuracy of 0.3℃and 2% RH. Surface temperature of the samples in a series of experiments under infrared lamps was measured with digital laser thermometer (TESTO-830-T2, Germany). To avoid exceeding of grain temperature beyond the standard level (70℃) a certain height (45 cm) for installation of the lamp was considered.

2.2 Modeling of the moisture ratio

To describe the moisture ratio as a function of drying time, seven different empirical and semi-empirical drying models were considered. These models which were also attempted by other researchers are presented in Table 1. The reader ought to know that the time is in minutes in the given models.

The moisture ratio was calculated as follow:

$$\mathrm{MR} = \frac{\mathrm{M}-\mathrm{M_e}}{\mathrm{M_0}-\mathrm{M_e}} \qquad (1)$$

Where MR, M_o , M and M_e are the moisture ratio, initial moisture content (kg/kg), the moisture content (kg/kg) at a specific time and the equilibrium moisture content (kg/kg),respectively. The equilibrium moisture content of grain is defined as the moisture content at which the internal grain vapor pressure is in equilibrium with the vapor pressure of the environment (Brooker et al., 1992).

2.3 Determination of the effective moisture diffusivity

Drying is a simultaneous heat and mass transfer process. The thermal energy required to evaporate moisture from the surface of a grain is provided by an external heat source, usually hot air. In addition, during infrared drying, heat is generated through the volume of grain kernels and leads to higher drying rate.

It has been reported that the moisture transfer from the interior to the surface of a kernel is occurred by diffusion. Several researchers have considered the diffusion as a dominant moisture transfer process during hot air-microwave drying of food materials (Abbasi Sourakiand Mowla, 2008; Ozbeland Dadali, 2007). The mathematical model employed in this study is based on Fick's law of diffusion (Brooker et al., 1992; DomyazandPala, 2003; Domyaz, 2005):

$$\frac{\partial M}{\partial t} = \nabla^2(\mathrm{D}_{eff}M) \qquad (2)$$

Where M is the moisture content of grain (kg/kg), t is time (s) and $\mathrm{D_{eff}}$ is the effective moisture diffusivity ($\mathrm{m^2/s}$). Using spherical coordinates, for a constant value of $\mathrm{D_{eff}}$ the Equation(3) can be written as:

$$\frac{\partial M}{\partial t} = (D_{eff}\frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r}) \qquad (3)$$

Where r is the radius of a spherical kernel (m).

The following initials and boundary conditions are usually applied to solve the Equation (3):

$t=0 \quad 0<r<R \quad M(r, 0) = M_0 \qquad (4)$

$r=0 \quad t>0 \quad \frac{\partial M}{\partial r} = 0 \qquad (5)$

$r=R \quad t>0 \quad -D_{eff}\frac{\partial M}{\partial r} = h_m(M_s - M_e) \qquad (6)$

The analytical solution of Equation (3) for a spherical grain kernel with the assumptions of negligible shrinkage, moisture migration being by diffusion, constant temperature and diffusion coefficient as well as constant infrared power intensity at the surface of grain kernel is as(Cranck, 1975):

$$\mathrm{MR} = \frac{6}{\pi^2}\sum_{\mathrm{n:1}}^{\infty}\left(\frac{1}{\mathrm{n}^2}\right)\exp\left(-\frac{\mathrm{n^2\pi^2D_{eff}t}}{\mathrm{r^2}}\right) \qquad (7)$$

The Equation (7) can be simplified to the first term of the series solution. It has been reported by several researchers that this simplification does not have a great influence on the accuracy of prediction (Domyaz and Pala, 2003):

$$MR = \frac{6}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}t}{r^2}\right) \qquad (8)$$

The Equation (8) can be written in a linearized form:

$$\ln(\mathrm{MR}) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\mathrm{n^2\pi^2D_{eff}t}}{\mathrm{r^2}}\right) \qquad (9)$$

This method has been demonstrated by several researchers (Ozbek & Dadli, 2007). Using Equation (9), one can estimate the effective moisture diffusivity by plotting the experimental data in terms of $\ln(\mathrm{MR})$, versus time.

2.4 Statistical modeling procedure

The non-linear regression analysis was performed using SPSS 16.0 software to determine the constants of the model. Eight general models existing in Table 1 were fitted to the experimental data. The adequacy of fitness was determined by considering the coefficient of determination R^2, Chi-square χ^2, Mean bias error (MBE) and Root mean square error (RMSE). The most appropriate model for MR was selected based on the highest value of R^2 and the lowest values for χ2,MBE and RMSE (Zare et al., 2009).

$$\chi^2 = \left[\frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2}{N-P}\right] \qquad (10)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pred,i} - MR_{\exp,i})^2\right]^{1/2} \qquad (11)$$

$$\mathrm{MBE} = [\frac{1}{N}\sum_{i=1}^{N}(MR_{exp} - MR_{pre})] \qquad (12)$$

Table 1Mathematical models applied to drying curves

Model No.	Model name	Model equation	References
1	Newton	$MR = \exp(-kt)$	Henderson, 1974
2	Page	$MR = \exp(-kt^n)$	Henderson, 1974
3	Henderson and Pabis	$MR = a. \exp(-kt)$	Chhinman, 1984
4	Logarithmic	$MR = a.\exp(-kt) +c$	Henderson, 1974
5	Two term	$MR = a.\exp(-k_0t)+ b.\exp(-k_1t)$	Henderson, 1974
6	Modified two term	$MR = a.\exp(-k_0t)+ b.\exp(-k_1t)+ c$	ZareandRanjbaran, 2012
7	Three term	$MR = a.\exp(-k_0t)+ b.\exp(-k_1t)+ \exp(-k_2t)+d$	Present study
8	Verma et al.	$MR = a.\exp(-kt)+ (1-a).\exp(-gt)$	Sharma and Prasad, 2001
9	Approximation of Diffusion	$MR=1+at+bt^2$	Zomorodianand Moradi,2010

3 Results and discussion

3.1 Mathematical modeling of thin layer drying of green peas

Curve fitting has been performed on the eight previously mentioned drying models to correlate the moisture ratio with the drying time and experimental conditions including air temperature and air velocity and infrared power intensity.

The corresponding constants as well as the values of R^2, χ^2,MBE and RMSE are given in Table 2. The values of these coefficients indicate that all models were capable of predicting the kinetics of drying of peas very well. However, among the models examined, the Three Term model was the most appropriate one with the values of 99.7%, 0.000121, 0.0000 and 0.01 for R^2 , χ^2 , MBE and RMSE , respectively. The experimental data of moisture ratio versus those predicted by Three Term model is shown in Figure 2 which indicates the suitability of the mentioned model.

Table 2 Statistical results of mathematical modeling of drying curve

Model name	Model coefficients	R^2	RMSE	MBE	χ^2
Newton	K=0.0056P-0.0011V+0.0002T-0.0012	93	0.0531	-0.0092	0.0028
Page	k=0.0099P-0.0027V+0.0002T+0.0097 n=0.0609P-0.0091V+0.0028T+0.6357	98.1	0.0279	0.0024	0.0008
Henderson andPabis	a=-0.0499P+0.0177V-0.0026T+1.0377 k=0.0046P-0.0009V+0.0001T-0.0002	95.4	0.0432	0.0019	0.0019
Logarithmic	a=0.0233P-0.0097V+0.0013T+0.6483 k=0.0085P-0.0016V+0.0003T+0.0011 c=-0.0768P+0.0261V-0.0031T+0.4215	98.8	0.0221	$-8.88E^{-11}$	0.0008
Two term	a=-0.0653P+0.0273V-0.0132T+0.9619 k_0=0.0012P-0.0001V-0.0001T+0.0042 b=0.0373P-0.0174V+0.0133T+0.0319 k_1=0.0127P-0.0027V+0.0003T+0.0014	99.4	0.0156	$5.79E^{-5}$	0.0003
Modified two term	a=0.4863P-0.0196V+0.0518T-1.5951 k0=0.0124P-0.0029V+0.0006T-0.0125 b=-0.4847P+0.0268V-0.0533T+2.3434 k1=0.0104P-0.0018V+0.0003T-0.0008 c=-0.0224P+0.0019V+0.0019T+0.2307	99.6	0.0122	$-4.46E^{-8}$	0.0002
Three term	a=-68.4625P+8.6775V+1.8005T-61.003 k_0=-0.0141P-0.0022V+0.0010T-0.0121 b=68.6222P-8.6638V-1.7727T+60.0294 k_1=-0.0141P-0.0022V+0.0010T-0.0125 c= -0.1273P-0.0059V-0.0231T+1.5171 k_2=0.0044P-0.0019V-0.0001T+0.0123 d=-0.0241P-0.0036V-0.0044T+0.4355	99.7	0.0109	$-2.94E^{-9}$	0.0001
Verma et al.	a=-0.0713P+0.0287V-0.0129T+0.9536 k=0.0010P-0.0001V-0.0001T+0.0042 g=0.0138P-0.0031V+0.0003T+0.0015	99.4	0.0159	$3.14E^{-5}$	0.0003
Approximation of Diffusion	a=0.1156P-0.0471V+0.0183T-0.1614 k=0.0122P-0.0025V+0.0002T+0.0057 b=0.0336P+0.0234V-0.0109T+0.4974	99.4	0.0156	$3.68E^{-5}$	0.0002

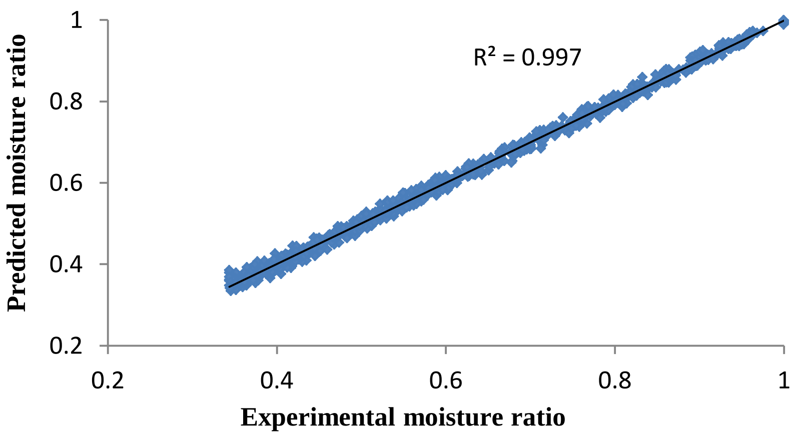

Figure 2 Experimental data versus predicted data of moisture ratio for the Three Term model

3.2 Effect of infrared power intensity on the drying kinetics of peas

Four different levels of infrared power intensities including 0, 0.2, 0.4 and 0.6 W/cm^2 were applied to determine the effect of infrared power on the drying kinetics of peas. The variation of the moisture ratio versus drying time for the experimental data and the Three Term model is illustrated for various infrared power densities at constant drying air temperature and air velocity of 40℃ and 1 m/s, respectively. It can be seen that as infrared power intensity is increased, the slope of drying curves becomes sharper. The drying time is decreased significantly in comparison with hot air drying of peas which reflects higher drying rates. By progressing of drying time, the effect of infrared power on the drying of peas decreases due to reduction of grains moisture content.

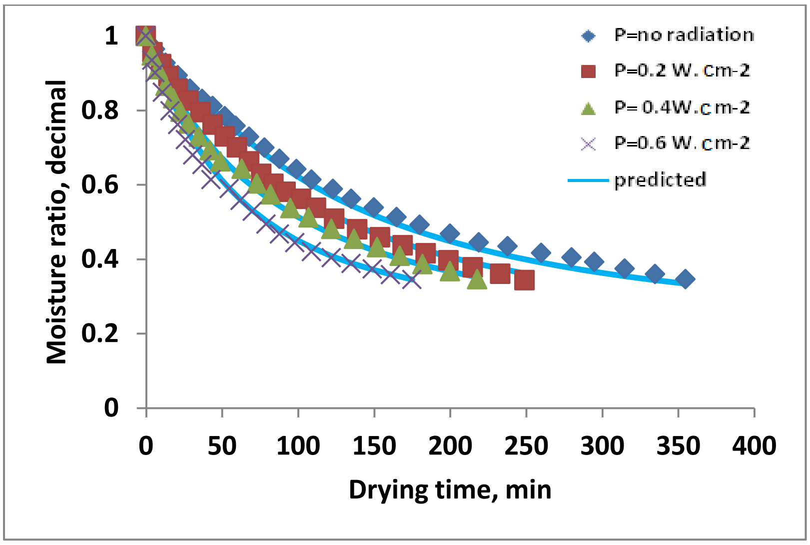

Figure 3 Variation of the moisture ratio versus drying time for the experimental data and Three Term model, at various infrared power densities for the drying air temperature of 40℃ and air velocity of 1 m/s

3.3 The effect of air temperature on drying kinetics of green peas

To investigate the effect of air temperature on drying kinetics of peas three different levels of air temperature including 30℃, 40℃ and 50℃ were used. Figure 4 shows the variation of moisture ratio versus drying time, for the experimental and predicted data at various air temperatures and infrared power intensity of 0.4 W/cm^2 and air velocity of 1 m/s.

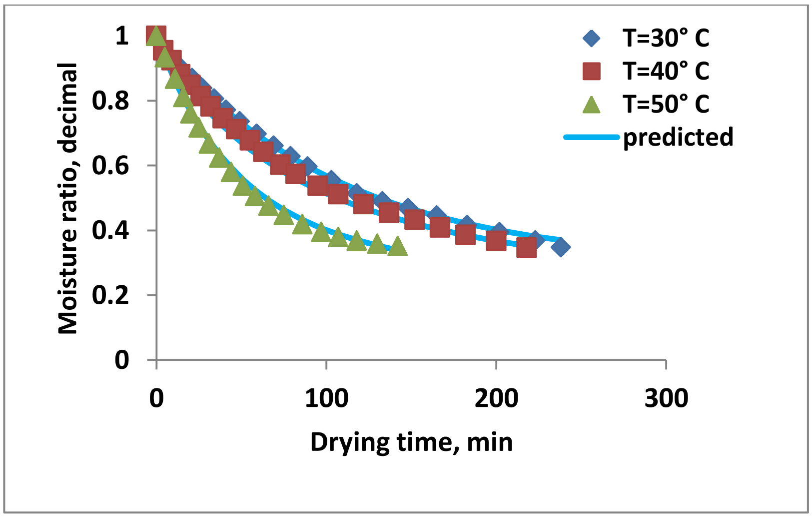

Figure 4 Variation of the moisture ratio versus drying time for the experimental data and the Three Term model, at various air temperatures for the constant infrared power intensity of 0.4 W/cm^2 and air velocity of 1 m/s

3.4 Effect of drying air velocity on the drying kinetics of green peas

To investigate the effect of drying air velocity on the drying kinetics of peas three different levels of air velocity including 0.5, 1 and 1.5 m/s were used. Figure 5 shows the variation of moisture ratio versus drying time, for the experimental and predicted data at various air velocity and infrared power intensity of 0.4 W/cm^{2}and air temperature of 50 ℃. Comparing Figures 3, 4 and 5, it can be seen that the moisture removal is more closely linked with the level of air velocity than air temperature and infrared power intensity rate.

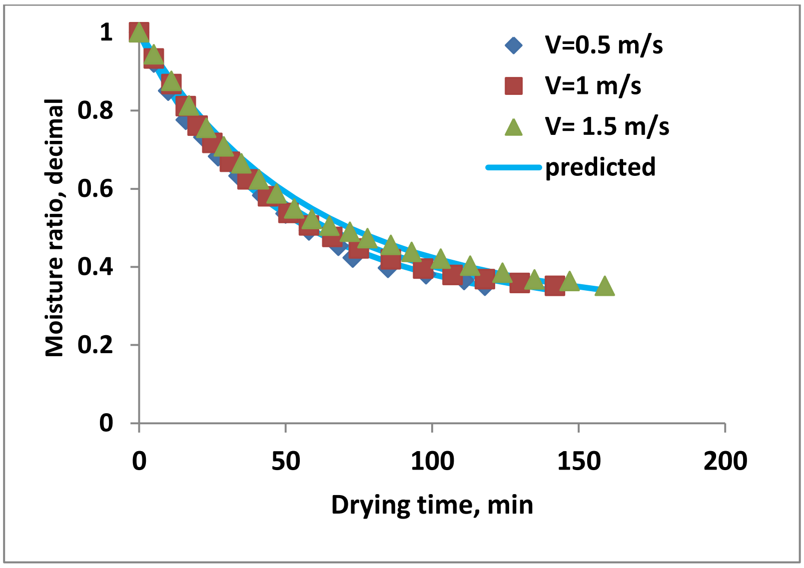

Figure 5 Variation of the moisture ratio versus drying time for the experimental data and the Three Term model, at the various air velocities for thei nfrared power intensity of 0.4 W/cm^2 and air temperature of 50 ℃

3.5 Determination of the effective moisture diffusivity

To estimate the effective moisture diffusivity for peas the natural logarithm of experimental moisture ratio, ln(MR), was calculated. The slope of the plot of ln (MR) versus drying time was calculated to obtain the effective moisture diffusivity by the following equation:

$$slope = \frac{\pi^2 D_{eff}}{r^2} \quad (13)$$

where r is the averaged radius of a single peas kernel (m).

The plot of ln(MR) versus drying time for different infrared power densities and at constant air temperature of 30 ℃ and air velocity of 0.5 m/s is illustrated in Figure 6. It can be seen that as the infrared power intensity increased the plot of ln(MR) becomes steeper which reflects higher moisture diffusivity through grains.

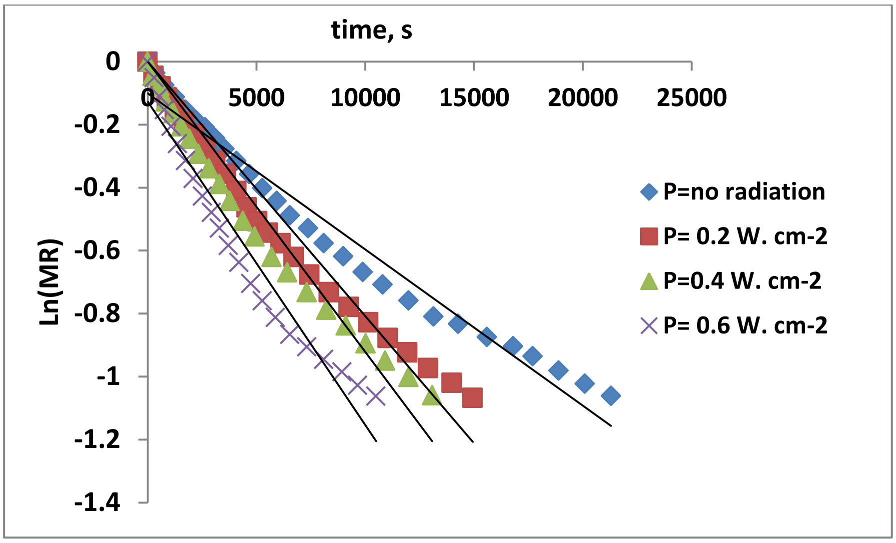

Figure6 Variation of ln(MR) versus drying time for different infrared power densities and constant air temperature of 40 ℃ and at velocity rate of 1 m/s

Furthermore, The plot of ln(MR) versus drying time for different air temperatures and the constant infrared power intensity of 0.4 W and constant air velocity of 1 m/s is shown in Figure 7. By applying higher air temperature the diffusivity coefficient increases (Doymaz, 2005; Madamba et al., 1996) and the drying time decreases.

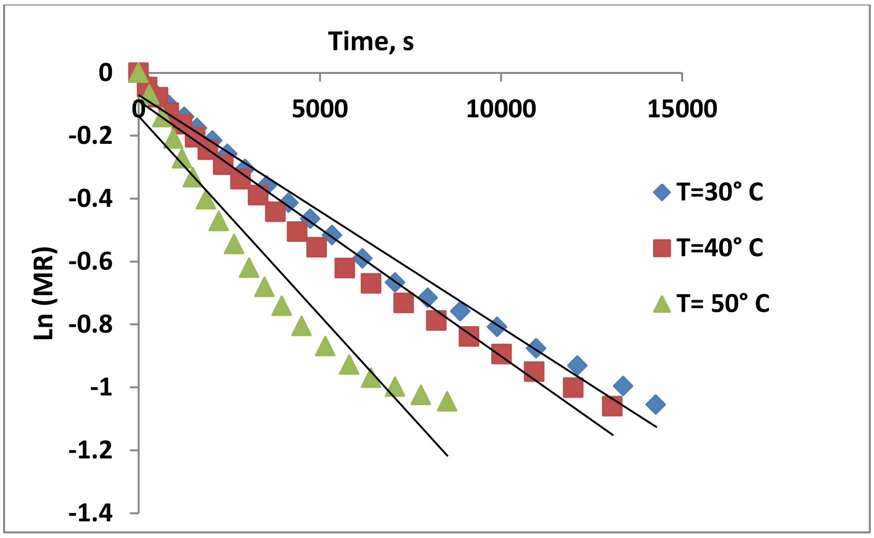

Figure 7 Variation of ln(MR) versus drying time for different air temperatures and constant infrared power intensity of 0.4 W and air velocity of 1 m/s.

The plot of ln(MR) versus drying time for different air velocity and at the constant infrared power intensity of 0.4 W/cm and air temperature of 50 ℃ is shown in Figure 8. A comparison between these curves indicates that the effect of infrared power on the effective moisture diffusivity is more than air temperature and air velocity.

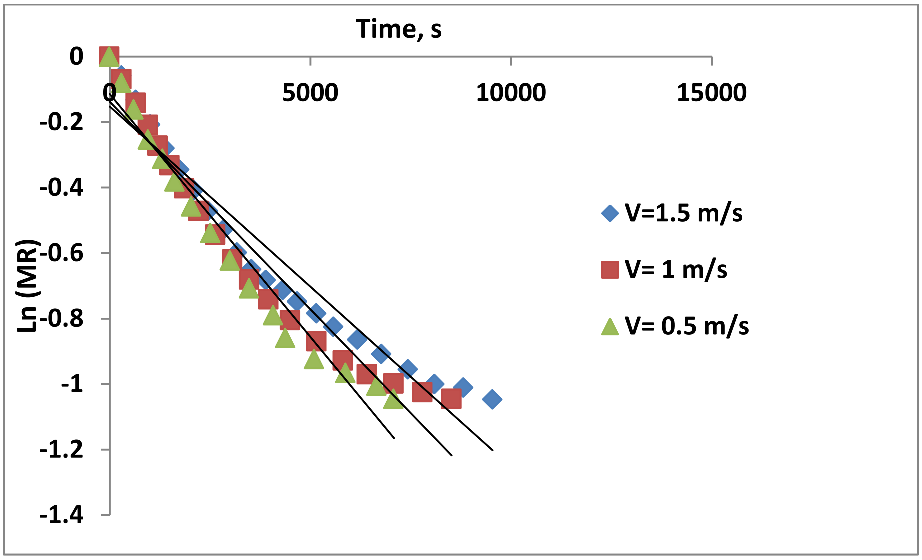

Figure 8 Variation of ln(MR) versus drying time for different air velocities and the infrared power intensity of 0.4 W/cm^{2}and air temperature of 50 ℃

The values of calculated effective moisture diffusivity for different infrared power densities, air temperatures and air velocities are summarized in Table 3. The values of R^2 reflect goodness of fitting. It can be seen that the values of D_{eff} have increased proportional to the increase of infrared power intensity and air temperature. However, the values of D_{eff} decrease with the decrease of air velocity when drying is performed without radiation but when infrared radiation is applied increasing air velocity causes a decrease in effective moisture diffusivity. Madamba et al. (1996) have reported that the values of D_{eff} for food materials are generally in the range of 10^{-11} to 10^{-9} m^2/s. In the present study the D_{eff} was calculated from $1.39\times10^{-10}$to 5.72×10^{-10}m^2/s.

The following empirical equation was obtained to estimate effective moisture diffusivity as a function of drying constants of the Three term model (k_0, k_1 and k_2),air temperature (T, ℃) , infrared power intensity (P, W/cm^2) and air velocity (V, m/s). The relationships of drying constants of Three Term model have been given in Table 2.

$$D_{eff}\times10^9 = a_0 k_0^2 + a_1 k_1^2 + a_2 k_2^2 + a_3 \quad (14)$$

Where,

a_0 =14222.1423P+ 28157.6682V – 6203.7809T +3484.9313

a_1 = -15506.6454P –27958.4668V +6037.8288T+ 551.8790

a_2 = -3482.2567P+342.9636V+68.7875T+7282.4274

a_3= -0.1633P+0.1663V+0.00011T-0.4447

The values of R^2 and X^2 are 99.79% and 0.00000, respectively

The relationship between the empirical and estimated values of effective moisture diffusivity is illustrated in Figure 9. It is shown that the Equation 13is capable of predicting the effecting moisture diffusivity reasonably.

Table 3 Calculated effective moisture diffusivity for different drying conditions

P, W/cm^2	V, m/s	T, ℃	Slope, 1/s	$D_{eff}\times10^9$, m^2/s	R^2
0	1.5	30	0.000045	0.139	97.5
0	1	30	0.000048	0.148	98.2
0	0.5	30	0.000051	0.158	98.9
0	1.5	40	0.000045	0.139	96.8
0	1	40	0.00005	0.155	97
0	0.5	40	0.000068	0.210	96.9
0	1.5	50	0.000085	0.263	96.3
0	1	50	0.000095	0.294	96.7
0	0.5	50	0.000104	0.322	96
0.2	1.5	30	0.000047	0.145	98.3
0.2	1	30	0.00005	0.155	96.1
0.2	0.5	30	0.000054	0.167	95.1
0.2	1.5	40	0.000066	0.204	99
0.2	1	40	0.000072	0.223	98
0.2	0.5	40	0.000083	0.257	98.8
0.2	1.5	50	0.000089	0.275	91.7
0.2	1	50	0.000098	0.303	94.2
0.2	0.5	50	0.000116	0.359	94.3
0.4	1.5	30	0.00007	0.217	96
0.4	1	30	0.000074	0.229	97.5
0.4	0.5	30	0.000081	0.251	98.1
0.4	1.5	40	0.000077	0.238	98.6
0.4	1	40	0.000081	0.251	97.7
0.4	0.5	40	0.000086	0.266	96.8
0.4	1.5	50	0.00011	0.34	93.1
0.4	1	50	0.000127	0.393	93.6
0.4	0.5	50	0.000148	0.458	95.7
0.6	1.5	30	0.000082	0.254	97.9
0.6	1	30	0.000092	0.285	98.3
0.6	0.5	30	0.000102	0.316	98.1
0.6	1.5	40	0.000095	0.294	95.7
0.6	1	40	0.0000103	0.319	95.1
0.6	0.5	40	0.000112	0.347	94.8
0.6	1.5	50	0.000144	0.446	97.3
0.6	1	50	0.000167	0.517	96.4
0.6	0.5	50	0.000185	0.572	97.2

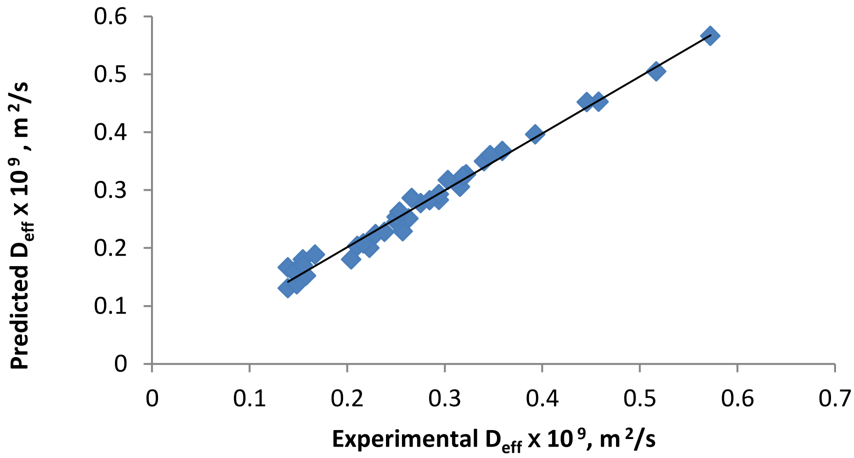

Figure 9 Experimental data versus predicted data of the effective moisture diffiusivity

4 Conclusions

The drying characteristics of green peas undergoing hot air-infrared heating were studied. Several empirical and semi-empirical models for predicting moisture ratio were fitted to the experimental data by the non-linear regression analysis using SPSS 16.0 software. The most appropriate model was the Three Term model with the values of 99.7%, 0.000121, 0.0000and 0.000121 for R^2, χ^2, MBE and RMSE, respectively. Applying infrared power in conjuction with hot air drying led to higher drying rate in comparison with the conventional hot air drying. The effective moisture diffusivity for several drying conditions were calculated in the range from 1.39×10^{-10}to5.72×10^{-10}m^2/s.

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Nomenclature

D_{eff}Effective moisturediffusivity, m/s^2

M Grain moisture content, kg/kg

mMass, kg

MBEMean bias error

MR Moisture ratio

P Infrared power intensity on the surface of material, W/cm^2

RRadius of kernel, m

rRadius, m

RMSE Root mean square error

T Temperature, ^{0}C

ttime, s

v velocity, m/s

Greek Letter

ρ Density, kg/m^3

χ^2Chi-square

Subscripts

0 Initial value

e Equilibrium

exp Experimental

pre Predicted

w Water